

THE HIGHEST ENERGY NEUTRINOS

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Abstract

Some neutrino predictions at the highest energies for a number of production mechanisms are comparatively reviewed in the light of future projects for neutrino detection.

1 Introduction

High energy neutrino detection is one of the most exciting challenges in particle astrophysics because neutrinos provide an alternative view of the Universe. Efforts to build such detectors in the forthcoming years [1] have granted an afternoon session on experimental high energy neutrinos in this conference. Two of these projects, AMANDA and Baikal, are already in operation [2]. The “km³” initiative, to instrument 1 km³ of water or ice with photodetectors, is the natural extension of the lower scale prototypes in view of the expected neutrino fluxes [3]. There is some more motivation in the “Pierre Auger Project” to build an air shower detector of 6000 km² in search for the highest energy cosmic rays [2]. The project is linked to neutrino astronomy in a double way. The production mechanism for the highest energy cosmic rays must make neutrinos at least in the interactions of the cosmic rays with the cosmic microwave background and, also, the array itself can be used to detect neutrinos of the highest energies [4].

I have been asked to review the possible sources of high energy neutrinos which is of course a pretty difficult task to do with justice in the light of all the activity in the field and the short space available. There is an excellent review provided by Ref. [1] where more details and complete references can be found, and a discussion of neutrino fluxes close to this one in Ref. [5]. Keeping this in mind I will restrict to some of the production mechanisms that predict the highest energy neutrinos. I will discuss their energy shape and comment on the

plausibility of the mechanisms proposed, which is of course pretty subjective, stressing the developments in models with neutrinos produced in the jets of Active Galaxies.

2 Neutrino production by cosmic rays

In the majority of mechanisms most neutrinos arise from the decay of charged pions (or kaons), produced in different type of high energy particle interactions. The pions can be produced in proton-proton or photon-proton interactions or alternatively from direct fragmentation of quarks, in the same way they are produced routinely in electron positron colliders. For relativistic pions in flight it can be assumed that, on average, each of the four leptons produced in the reaction and subsequent muon decay carries one fourth of the parent energy.

The existence of high energy cosmic rays leaves little doubt about the actual production of neutrinos in their interactions with well understood targets. Atmospheric neutrinos fall in this category and are known to within about 10% certainty at energies below 1 PeV [1]. These neutrinos constitute the background for observation of other neutrinos sources. Their flux is zenith angle dependent because of the competition between interaction and decay of the parent pions. The vertical and horizontal atmospheric neutrino fluxes are shown in Fig 1A. At high enough energies the Lorentz expanded lifetime of the pion leads to more pion interactions decreasing the relative number of neutrinos to their parent pions. This causes that neutrinos from the decays of charmed particles (that have considerably shorter lifetimes), the “prompt” neutrinos, dominate the atmospheric flux above some unknown energy somewhere above 100 TeV. A typical prompt neutrino prediction [7] is illustrated in Fig. 1A. The uncertainty in the prompt component is due to the poorly known charm production cross section.

Cosmic rays must also interact with nucleons in the galaxy, such as dust, molecular clouds or compact objects like the sun. The interactions with the galactic disk matter are most relevant and do not have large uncertainties [5]. The results [6] are also shown in Fig. 1A evidencing that these neutrinos dominate the conventional atmospheric flux in the energy region where the prompt neutrinos are expected. This difficulties their possible identification but it is hoped that the prompt neutrinos can be indirectly determined by measuring the atmospheric prompt muons which are produced by the same mechanism [7].

The interactions of cosmic rays with the cosmic microwave background is also an unavoidable source of neutrinos assuming the higher energy cosmic rays are of extragalactic origin and hence universal. This is supported by the non observation of cosmic ray anisotropies at high energies. Several groups that have calculated these fluxes[1, 8, 9] and their results are within a couple of orders of magnitudes, mostly depending on the different assumptions made. I will refer to these as GZK neutrinos to stress their relation to the cosmic ray

energy cutoff. For this calculation the cosmic ray spectrum has to be estimated at the production site. This implies extrapolating to energies above the maximum currently observed ($\sim 3 \cdot 10^{20}$ eV) and making some assumptions about the evolution of cosmic ray luminosity with cosmological time. The production mechanism has to be integrated over time (or redshift) up some earlier epoch (z_{ult}) which is expected to be provided by the Galaxy formation era ($z_{ult}=2-4$). These flux predictions are all fairly flat because the proton photon interaction cross section has a threshold behavior at the resonant Δ production. Most neutrinos are produced with energies about a factor 20 (see next section) below the Greisen-Zatsepin-Kuz'min cutoff energy $\sim 10^{20}$ eV. Depending on (z_{ult}) the interactions of the highest energy neutrinos with the cosmic neutrino background can play a more important role altering their shapes in the highest energy region. Fig. 1A includes some of these calculated fluxes indicating the levels of uncertainty.

Regardless of the uncertainties in the GZK neutrinos, all these mechanisms are certain, at least in the sense that if by some means they were found not to be there, the hypothetical implications of such non-discovery would have a larger impact in physics and/or cosmology than their actual observation.

3 Neutrino production in objects known to exist

I will now consider another category of neutrino fluxes which is plausible in the sense that they can be produced in objects that we know exist. Some of them can be galactic such as accretion in binary systems, supernova remnants, but those reaching to highest energies are likely to be extragalactic. The most representative are Active Galactic Nuclei (AGN), and possibly Gamma Ray Bursts (GRB), although the origin of GRB's is still in debate. AGN have also been dedicated a good part of a morning session in this conference. The recent detection of GeV gamma rays from over sixty AGN by the Compton Gamma Ray Observatory (GRO)[10] together with the detection of TeV photons from three other nearby AGN with the imaging technique in Cherenkov telescopes [11], place them at the forefront of particle astrophysics. These objects have also been proposed as sites for acceleration of the highest energy cosmic rays, as they have physical parameters which are dimensionally compatible with high energy cosmic rays. For all these reasons I will discuss them in some detail.

AGN are the most luminous objects that we observe. They display remarkable jets that stream highly collimated out of their cores to distances of several parsecs. They also show inner structure with superluminal motion, which is naturally explained by particle flows with bulk relativistic speeds. These jets observed in the radio band are very likely due to synchrotron emission from electrons that are accelerated along the jet axis. If protons are accelerated along with the electrons as some authors claim, then neutrino production is unavoidable because of photoproduction of pions in the ambient radiation field

which is close to the Eddington limit. Earlier models of such fluxes considered their production in AGN cores [12] but the recent identification of all gamma ray detections with blazars [13], believed to be AGN with their jets pointing towards us [14], has shifted the interest to models in which protons are accelerated in the jets [15, 16]. In these models the neutrinos are Lorentz boosted to energies higher than in AGN cores, what has important implications for their detection.

The models can be dimensionally explained with 3 simple assumptions [17]: protons are accelerated in the jets with an E^{-2} spectrum as expected in shock acceleration, the maximum energy for the protons is 10^{20} eV and, finally, the target photon density behaves as a negative power law $E^{-\alpha}$ (for AGN in the broad infrared to X-ray band α is typically around 1).

It can be shown by simple energetics of the photopion production that the ratio of neutrino to photon luminosities is roughly 3/13. The result is obtained using a cross section for π^0 production twice that for π^+ , assuming each neutrino has exactly one fourth of the π^+ energy and adding a small correction for pair production [1]. The neutrino energy flux can be obtained scaling the measured GeV to TeV gamma ray energy flux for Markarian 421, $J_\gamma \sim 5 \cdot 10^{-10} \text{ TeV cm}^{-2} \text{ s}^{-1}$ with this ratio to get $J_\nu \sim 10^{-10} \text{ TeV cm}^{-2} \text{ s}^{-1}$. Mrk 421 is a nearby blazar which has been well established by GRO and by two Cherenkov telescopes. The shape of the neutrino spectrum here is also finally obtained by the threshold behavior of the photoproduction cross section at the Δ resonance. For a given proton energy E_p the required energy of the target photon for resonance scales as E_p^{-1} . Combining the proton spectrum and the target photon density spectrum at resonance gives a power law $E_\nu^{-2+\alpha}$ with maximum neutrino energy of $2 \cdot 10^{18} \text{ eV} \sim 0.25 < x_F > E_p^{max}$ (where $< x_F > = 0.2$ is the average Feynman- x for photopion production at resonance). Provided $\alpha > 0$, the total energy flux, the spectral index and the maximum energy determine the flux uniquely because then the energy integral is insensitive to the lower limit. The shape of the spectrum obtained is very close to that predicting in the two alternative models for acceleration in AGN jets. It is a straightforward matter to rescale the flux with some factor of order 100 sr^{-1} corresponding to the equivalent number of Mrk421 flux-like AGN per steradian [17], to get also the order of the normalization for the diffuse neutrino flux from all AGN. The exercise stresses the important assumptions in the models and explains the overall shift of energy to the 10^{18} eV region as illustrated in Fig. 1B where the two predictions for acceleration of protons in jets are compared to neutrinos from their cores.

4 Exotic neutrino sources

Lastly there is a third category of more exotic sources whose existence has only been postulated on theoretical grounds. Such is the case of Primordial Black Holes, decays of topological defects or WIMP annihilation. Topological

defect (TD) scenarios arise in grand unified theories of particle interactions with spontaneous symmetry breakdown. They are naturally formed as some field vacuum goes through a phase transition to a new degenerate vacuum as the Universe cools down in its expansion. Different regions of space go to different vacua and the net distribution may evolve later into a vacuum field with non-trivial topology, surrounding a point (monopole), a line (string) or a surface (domain wall). These cosmological objects accumulate energy and when they interact with themselves or with other objects of their own nature, they annihilate liberating large amounts of energy in the form of X particles, the Gauge bosons of the underlying grand unified theory. TD scenarios have been recently heavily discussed as the possible origin of the highest energy cosmic rays. Several authors have normalized the defect abundances to cosmic or gamma ray measurements and bounds [18, 19, 20]. Such a mechanism avoids the conceptual difficulties involved in accelerating protons or nuclei in our vicinity to energies above the Greisen Zatsepin Kuz'min cutoff.

The models are however very uncertain because they are significantly affected by a variety of parameters besides the normalization itself. In general they extend to very high energies dictated by the mass of the X particles expected to be of order $10^{14} - 10^{16}$ GeV. The shape of the fluxes predicted are very flat and are somewhat different depending on the behavior of the time evolution of the effective injection rate of X particles. This is usually parameterized as t^{p-4} with $p = 0$ for superconducting cosmic strings, $p = 1$ for monopoles and cosmic strings and $p = 2$ for constant injection rates in comoving volume [18]. The main uncertainty in the neutrino spectrum shape is due to the fragmentation function assumed which is used with large extrapolations. Moreover the normalization to cosmic or gamma rays is also subject to uncertainties due to the interactions of the cosmic rays in their propagation, mostly with the poorly known extragalactic B fields [20]. Fig. 1B illustrates some of the produced neutrino fluxes by different authors and for different assumptions.

5 Experiment: present and future

There are already some experimental results in the form of upper bounds provided by three types of experiments. One is from underground muon detectors, of which Frèjus provides the most stringent limit [21], the other two are from Extensive Air Shower detectors, particle detector arrays such as AKENO and EAS-TOP and a fluorescence light detector, Fly's Eye. Their results are not straightforward to convert to bounds on differential neutrino spectra because the conversion involves an assumption on the shape of the neutrino spectrum. Moreover there are important uncertainties in the high energy neutrino cross sections, besides the usual experimental uncertainties associated with each of the experiments. Fig. 2 compares atmospheric fluxes, some TD fluxes and fluxes from AGN jets to these bounds. Some of the results are clearly in conflict with experiment. Some Superconducting Cosmic String models are ruled

Table 1: Expected neutrino event rates in the Pierre Auger Project for several fluxes.

ν source	Range of yearly event rates
AGN-cores [12]	0.2-1.5
AGN-jets [15]	2-7
GZK $z_{ult} = 4$ [9]	0.1-0.4
TD $p = 1.5$ [18]	2-10

out by underground detectors and by the muon poor horizontal shower bound from AKENO [22].

Our discussion of fluxes has stressed the importance that the highest energy neutrinos have for the future of this field, particularly in the light of recent theoretical developments. Possibly the largest challenge is provided by the low level of the GZK neutrinos which should however be there. The shift of interest to the higher energies has some important implications for detection because of the rise in the neutrino cross section. At these energies the Earth will be completely opaque to neutrinos so underground muon detectors will have to look for horizontal showers or vertical downgoing showers. Moreover the showers will be in dense media where interesting new effects such as the Landau-Pomerančuk-Migdal will markedly show up and difficult the energy measurements. This will certainly affect the optimal separation of their optical modules. A shift to neutrino energies in the 10^{18} eV and above adds considerable more interest to the alternative techniques such as the detection of horizontal air showers with giant array detectors like the Auger project or the yet unproven detection of the coherent radio pulses from the excess charge in the showers[23]. In table 1 some preliminary results of expected neutrino event rates in the Pierre Auger project for a number of the discussed fluxes are reported [4].

Hopefully in the near future we will have some neutrino events. Underground muon detectors with a 1 km^2 surface area will have very enhanced acceptances for muon neutrinos because of the long range of the muon produced in charged current interactions, and can detect neutrinos for energies starting from roughly 100 GeV or so. The Pierre Auger Project could have an acceptance comparable to 1 km^3 for contained events and electron neutrinos. Lastly the radio technique if proven to be viable may open new possibilities of exploring even larger energies and lower fluxes. The complementarity between each of the detector types would no doubt constrain any hypothetically detected flux and allow the extraction of much more precise information.

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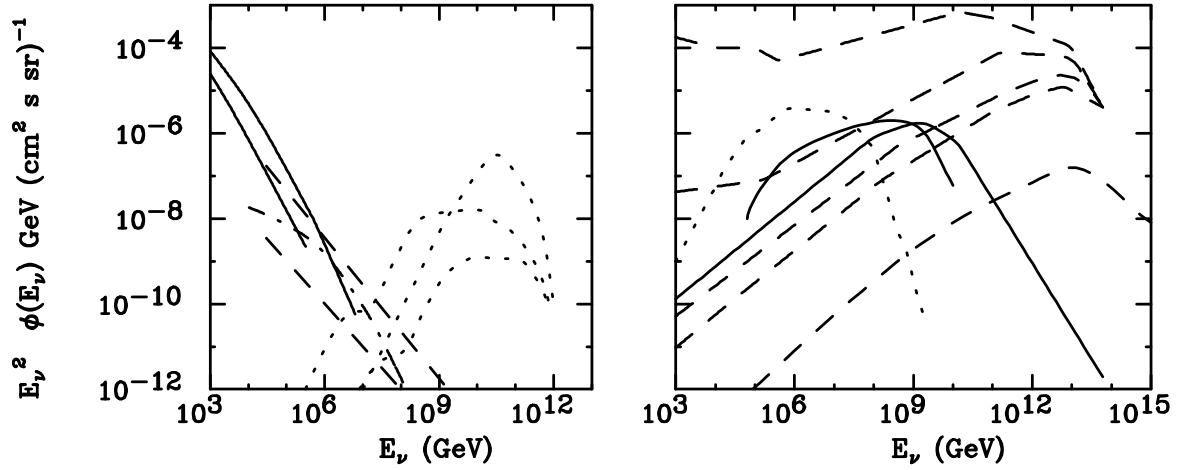


Figure 1: Neutrino flux predictions (from top to bottom where listed): 5 1A Conventional atmospheric for 90° and 0° zenith angles (solid) and prompt (dot dashes) [7], from CR interactions with the galactic matter for 0° and 90° galactic latitude (dashes) [6] and GZK neutrinos (dots) for $z_{ult} = 2.2$ [8], and $z_{ult} = 4$ and $z_{ult} = 2$ for ref. [9]. Fig 1B From AGN jets (solid) (from left to right refs. [16] and [15]), from AGN cores [12] (dots) and TD decays models with $p = 0, 0.5, 1$ and 1.5 in ref [18] and for $p = 1$ and $m_X = 2 \cdot 10^{25}$ eV in ref. [19] (dashes).

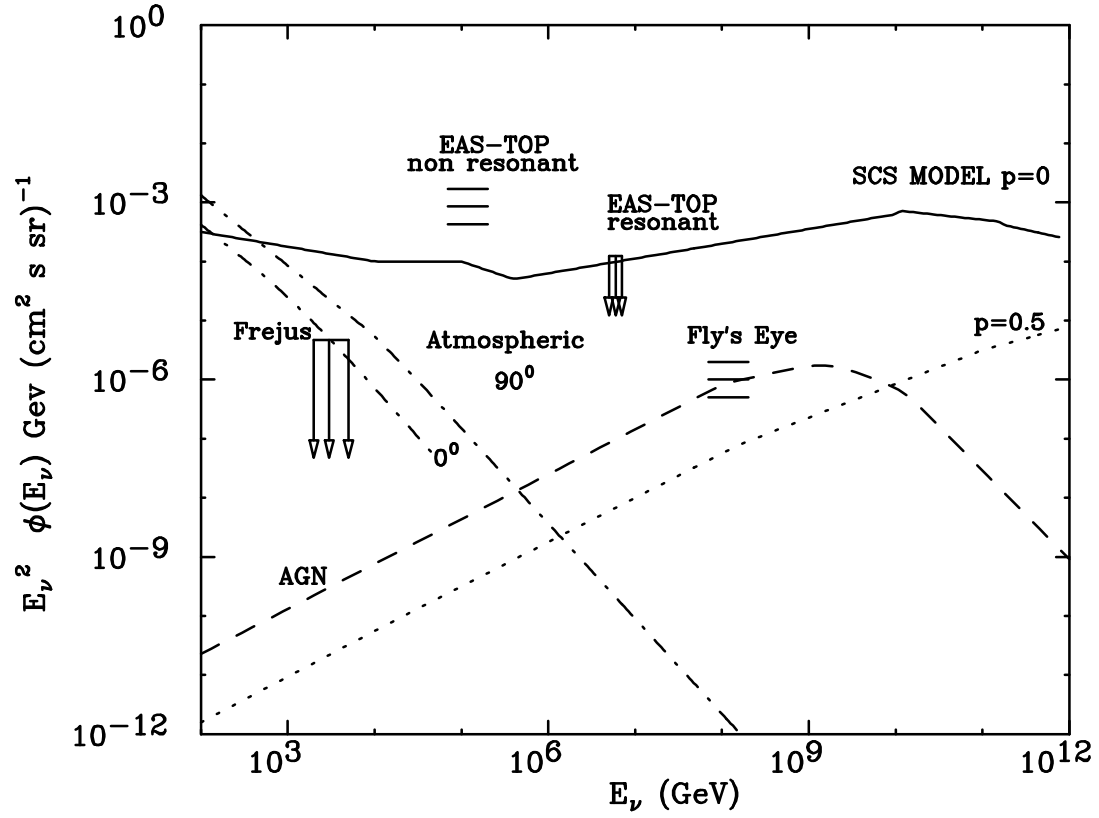


Figure 2: Neutrino flux predictions compared to existing bounds from experiment. Parallel lines indicate the uncertainty associated to the spectral index assumed for the conversion to a flux bound.